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(54) **REDUCED FREE-CHARGE CARRIER LIFETIME DEVICE**

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H01L 29/739 (2006.01)
H01L 21/8222 (2006.01)

(52) **U.S. Cl.** **257/577**; 257/590; 257/E21.383; 257/E29.197; 438/328; 438/378

(58) **Field of Classification Search** 257/577, 257/590, 143, 156, 376, E21.383, E29.197; 438/328, 378, 370

See application file for complete search history.

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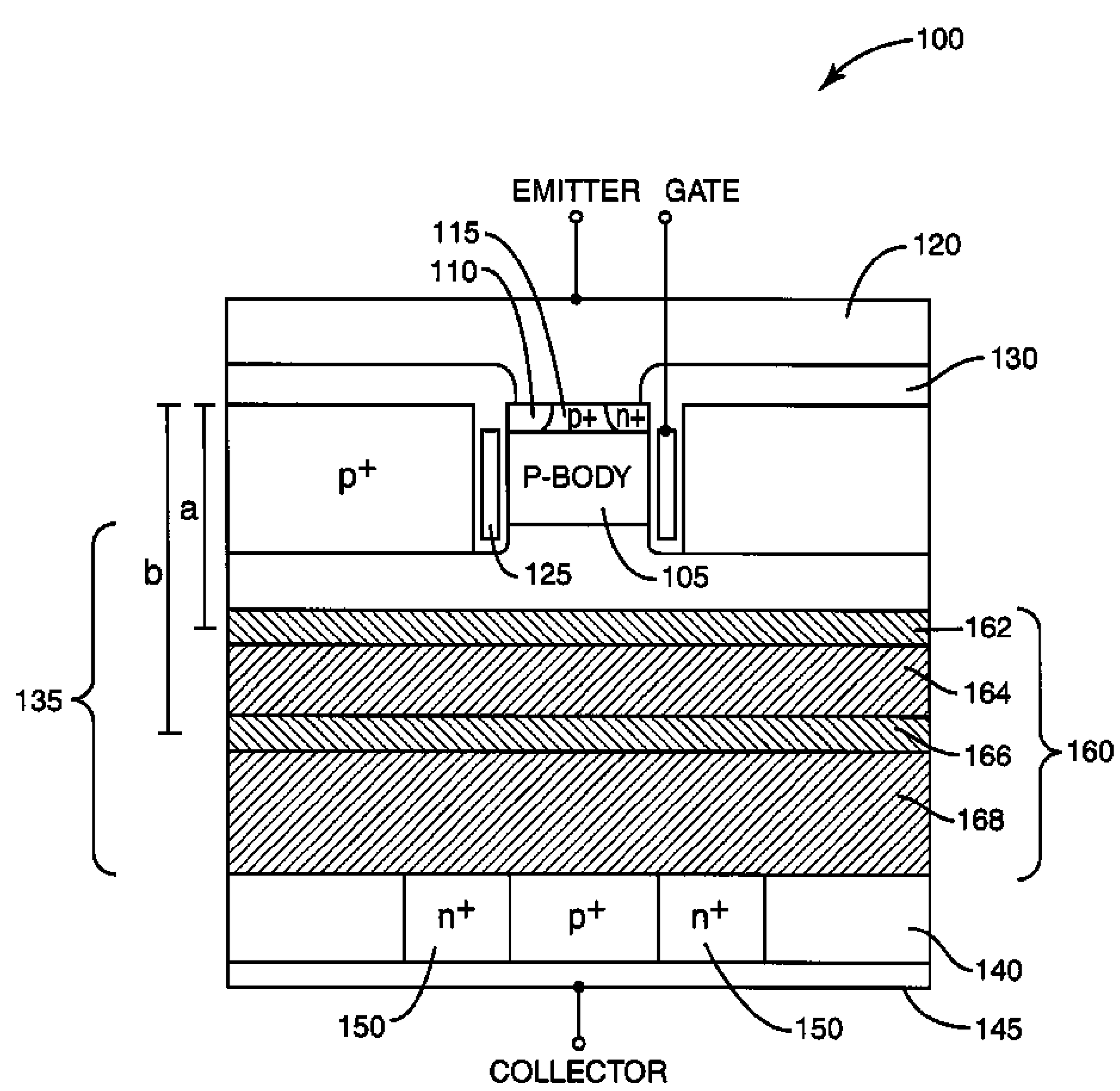
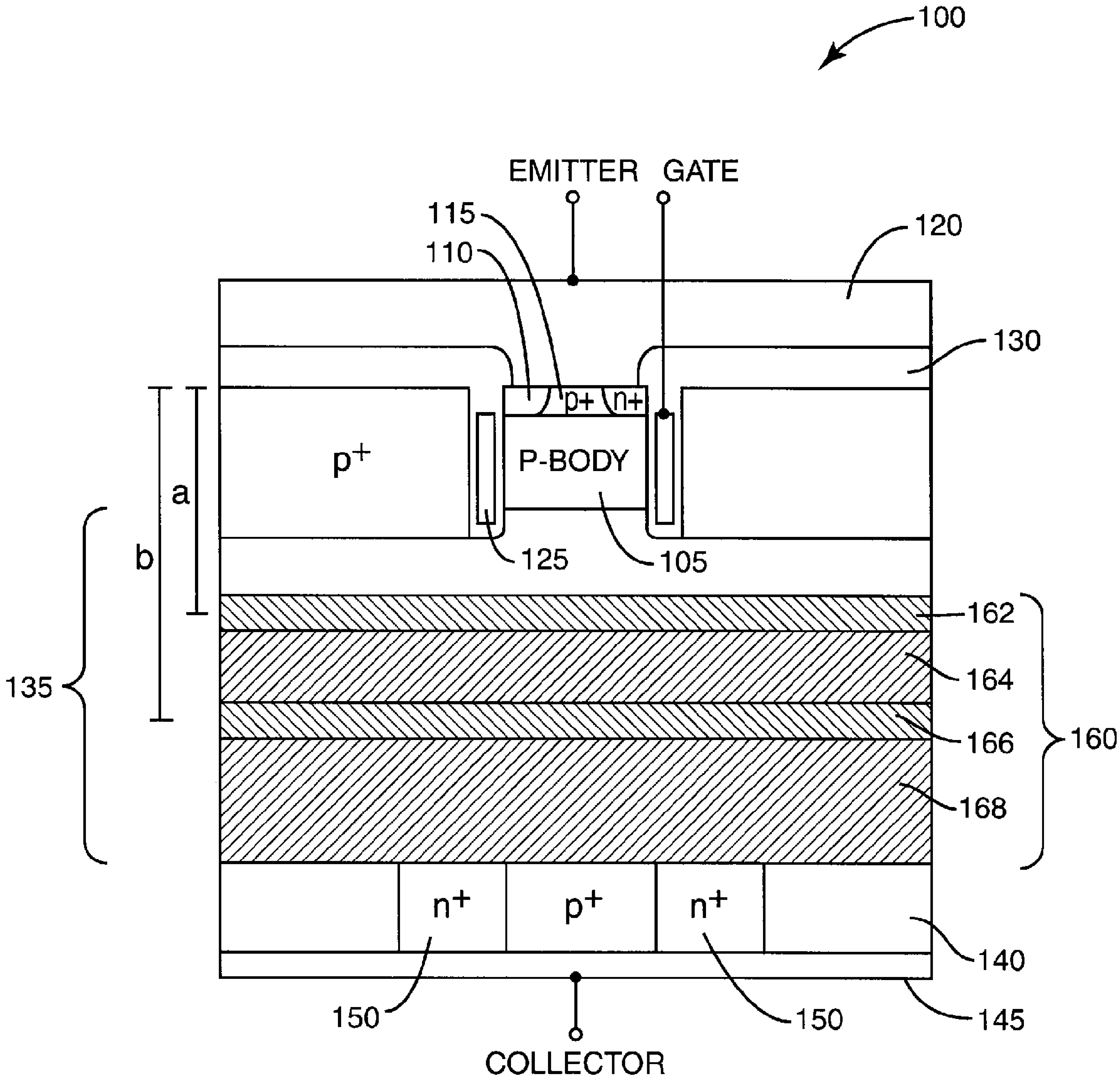
(57) **ABSTRACT**

According to one embodiment, a semiconductor device comprises a body of a first conductivity type having a source region and a channel, the body being in contact with a top contact layer. The device also comprises a gate arranged adjacent the channel and a drift zone of a second conductivity type arranged between the body and a bottom contact layer. An integrated diode is formed partially by a first zone of the first conductivity type within the body and being in contact with the top contact layer and a second zone of the second conductivity type being in contact with the bottom contact layer. A reduced charge carrier concentration region is formed in the drift zone having a continuously increasing charge carrier lifetime in the vertical direction so that the charge carrier lifetime is lowest near the body and highest near the bottom contact layer.

19 Claims, 12 Drawing Sheets

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p+
n+
p+
P-BODY
a
b
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164
166
168
160
135
n+
p+
n+
140
150
150
145
COLLECTOR

FIG. 1

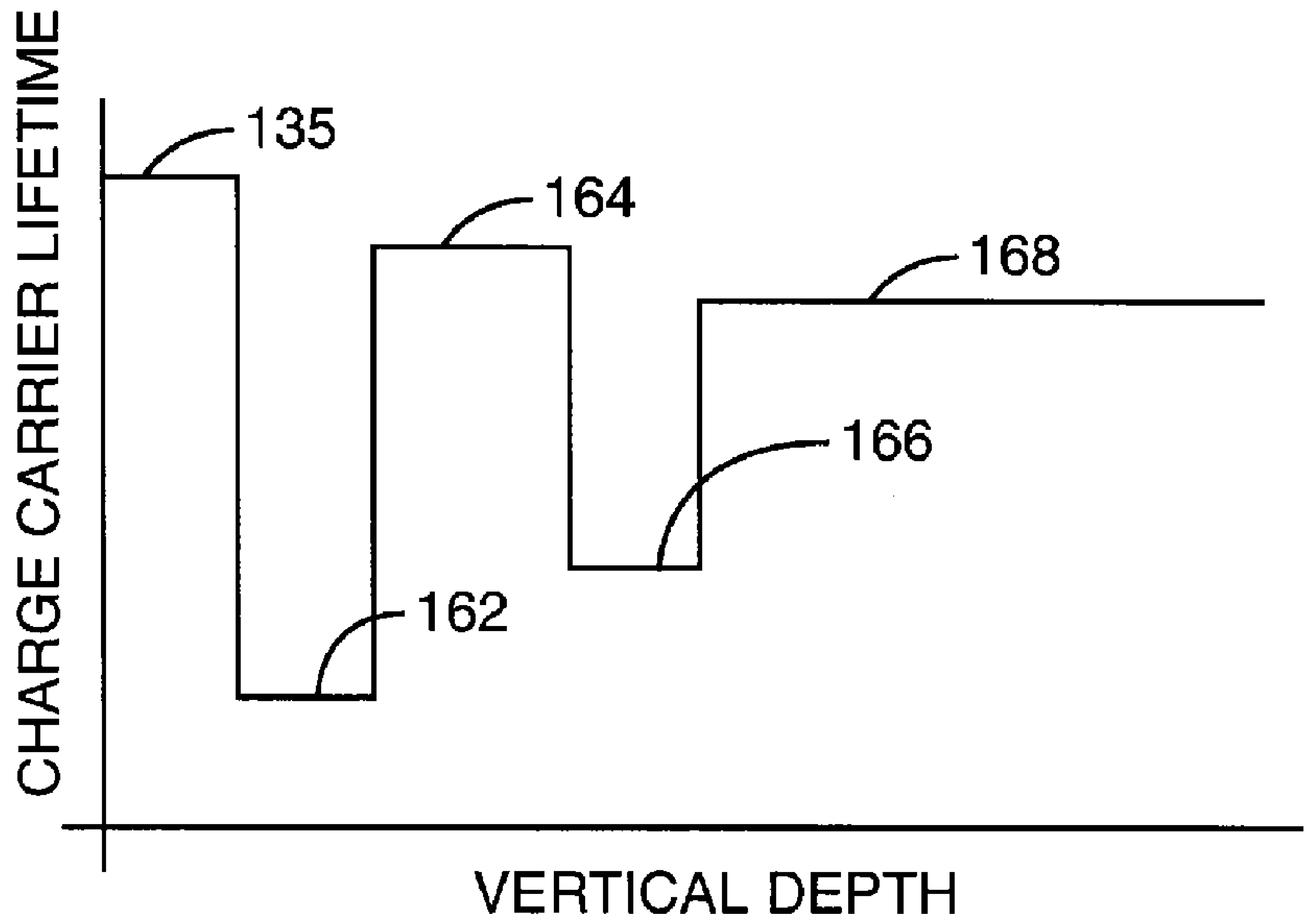
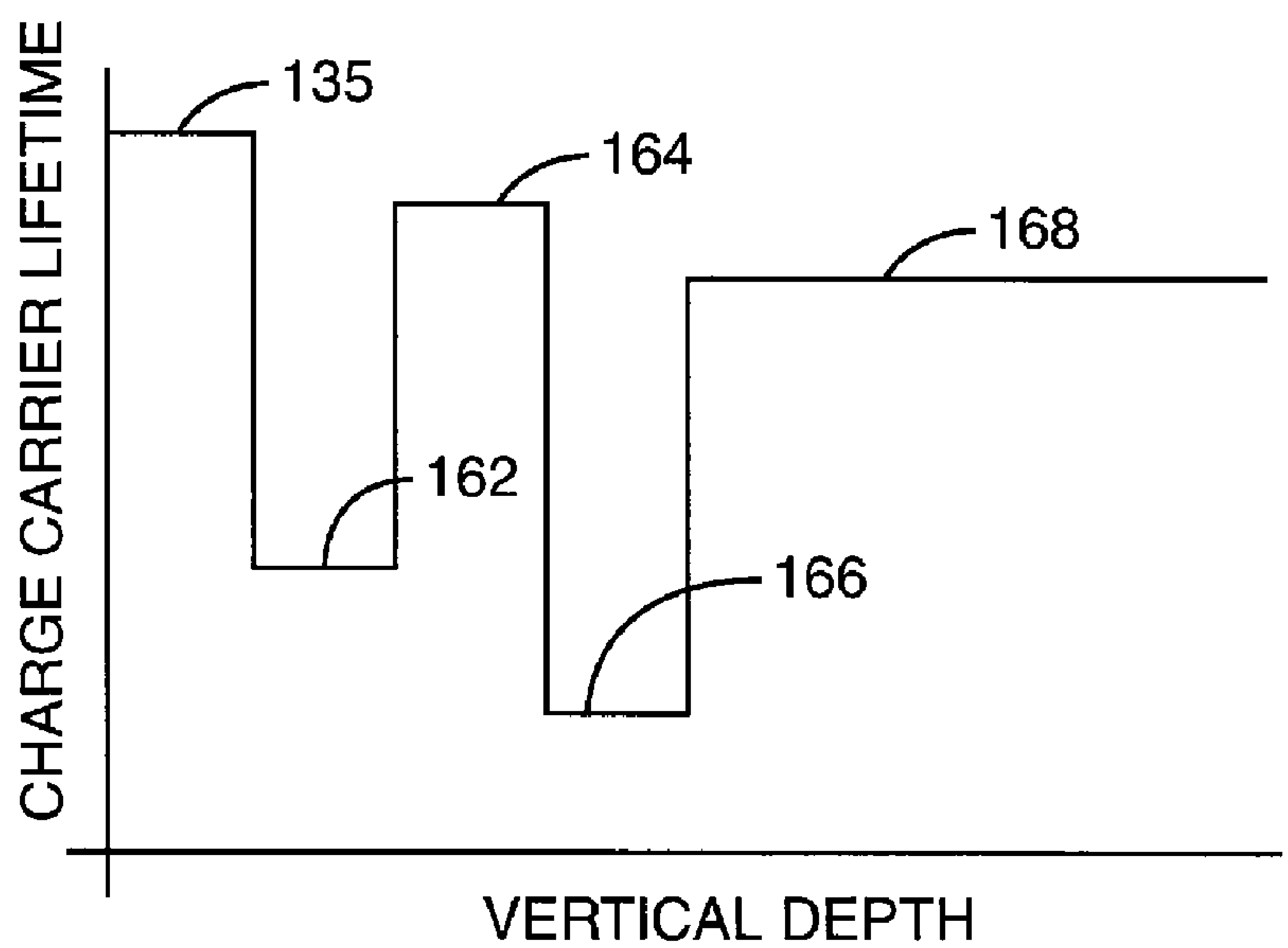

CHARGE CARRIER LIFETIME
135
164
168
166
162
VERTICAL DEPTH

FIG. 2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135
164
168
162
166
VERTICAL DEPTH

FIG. 3

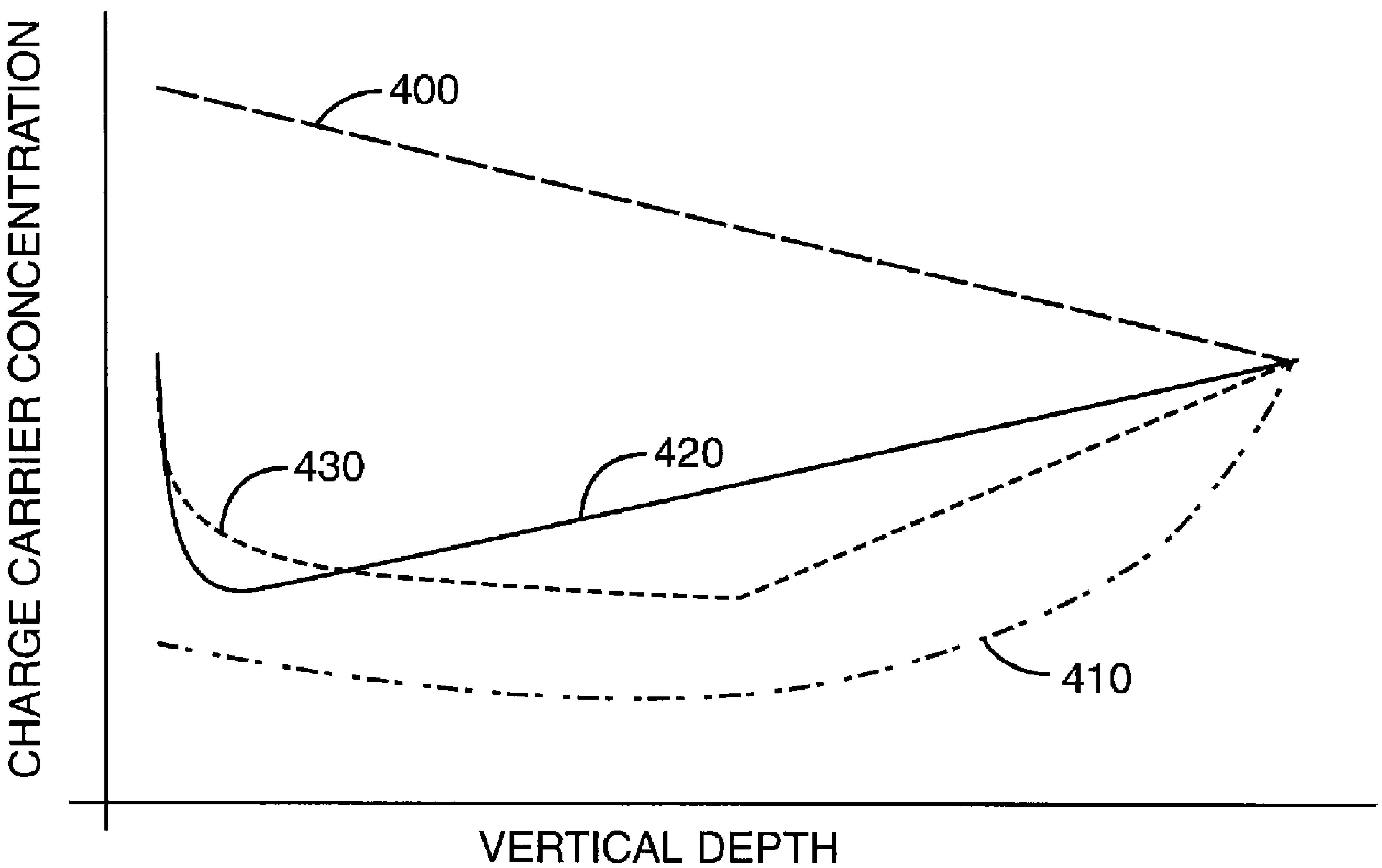

CHARGE CARRIER CONCENTRATION
400
430
420
410
VERTICAL DEPTH

FIG. 4

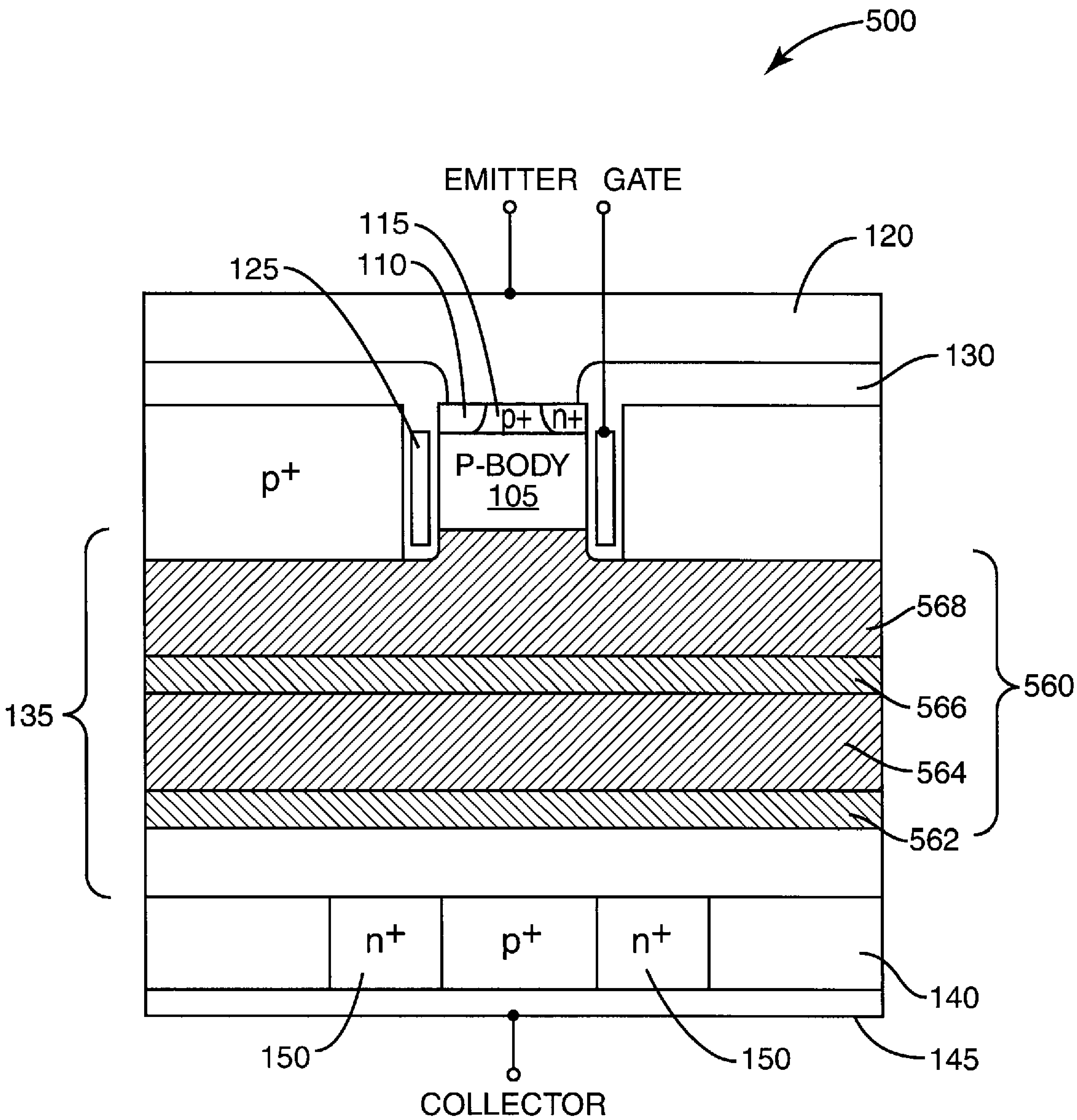

500
EMITTER
GATE
115
110
125
120
130
p+
n+
p+
P-BODY
105
568
566
564
562
560
135
n+
p+
n+
140
150
150
145
COLLECTOR

FIG. 5

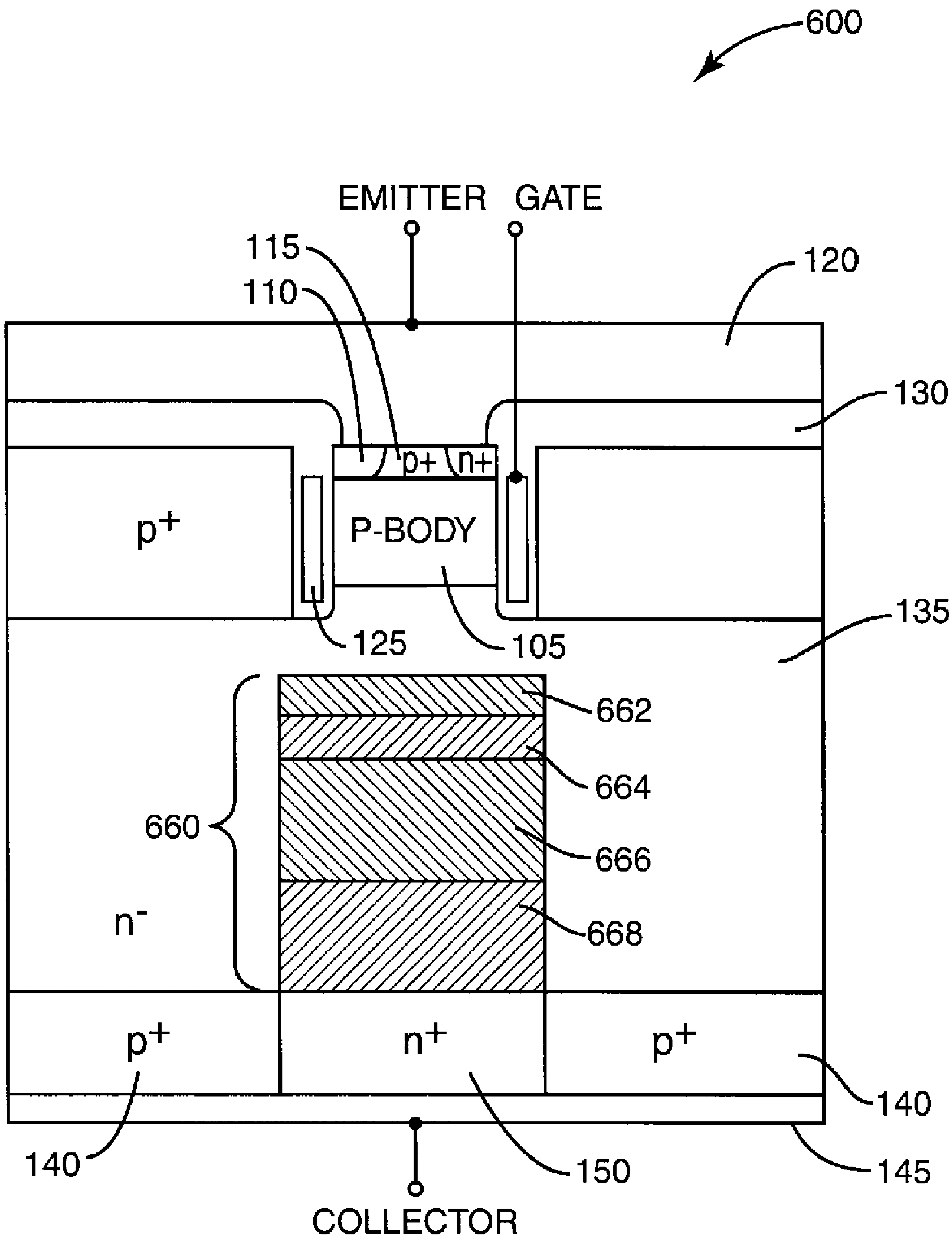

600
EMITTER
GATE
115
110
120
130
p+
n+
p+
P-BODY
125
105
135
662
664
666
668
660
n-
p+
n+
p+
140
140
150
145
COLLECTOR

FIG. 6

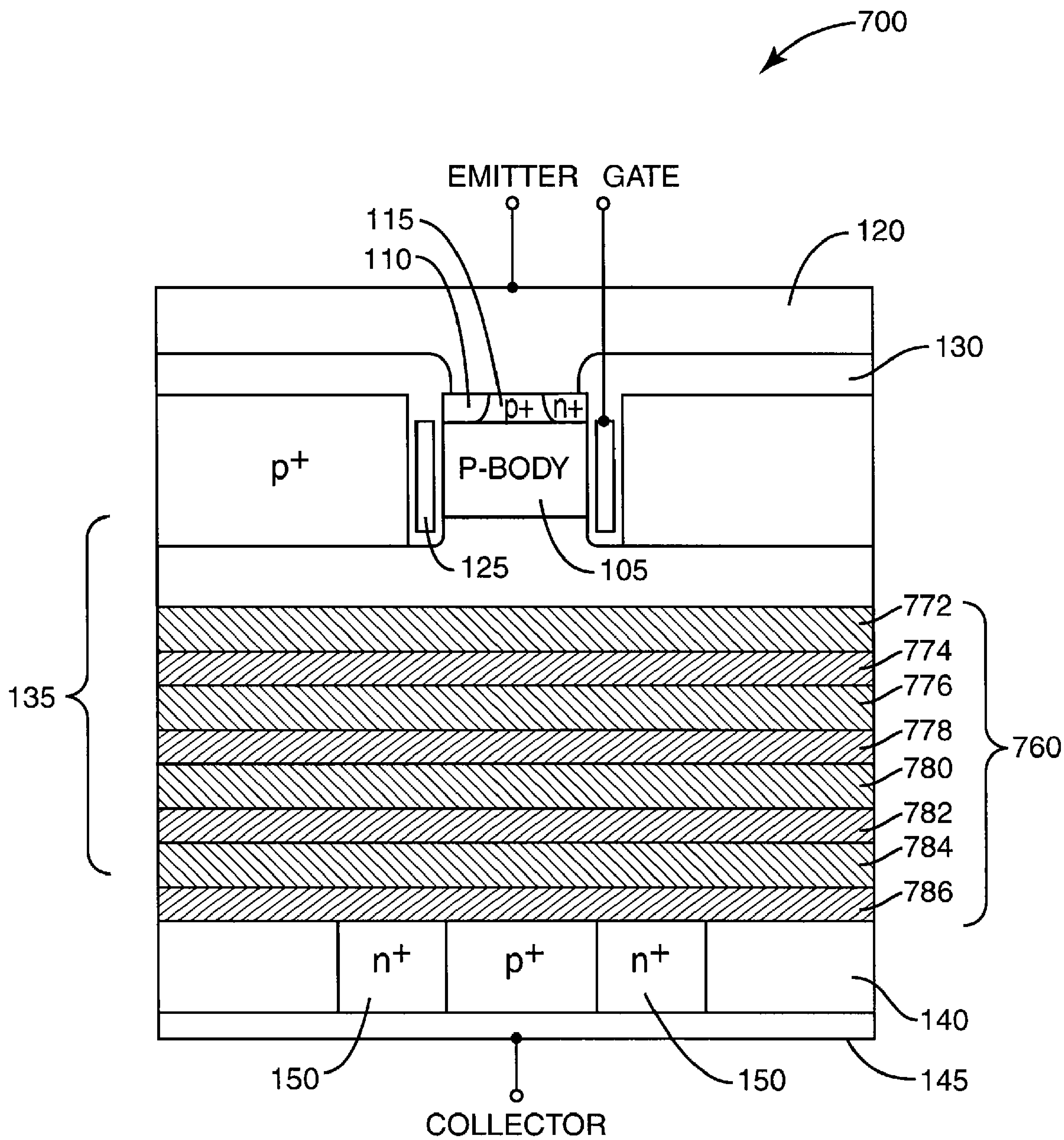

700
EMITTER
GATE
115
110
120
130
p+
n+
p+
P-BODY
125
105
135
772
774
776
778
780
782
784
786
760
n+
p+
n+
140
150
150
145
COLLECTOR

FIG. 7

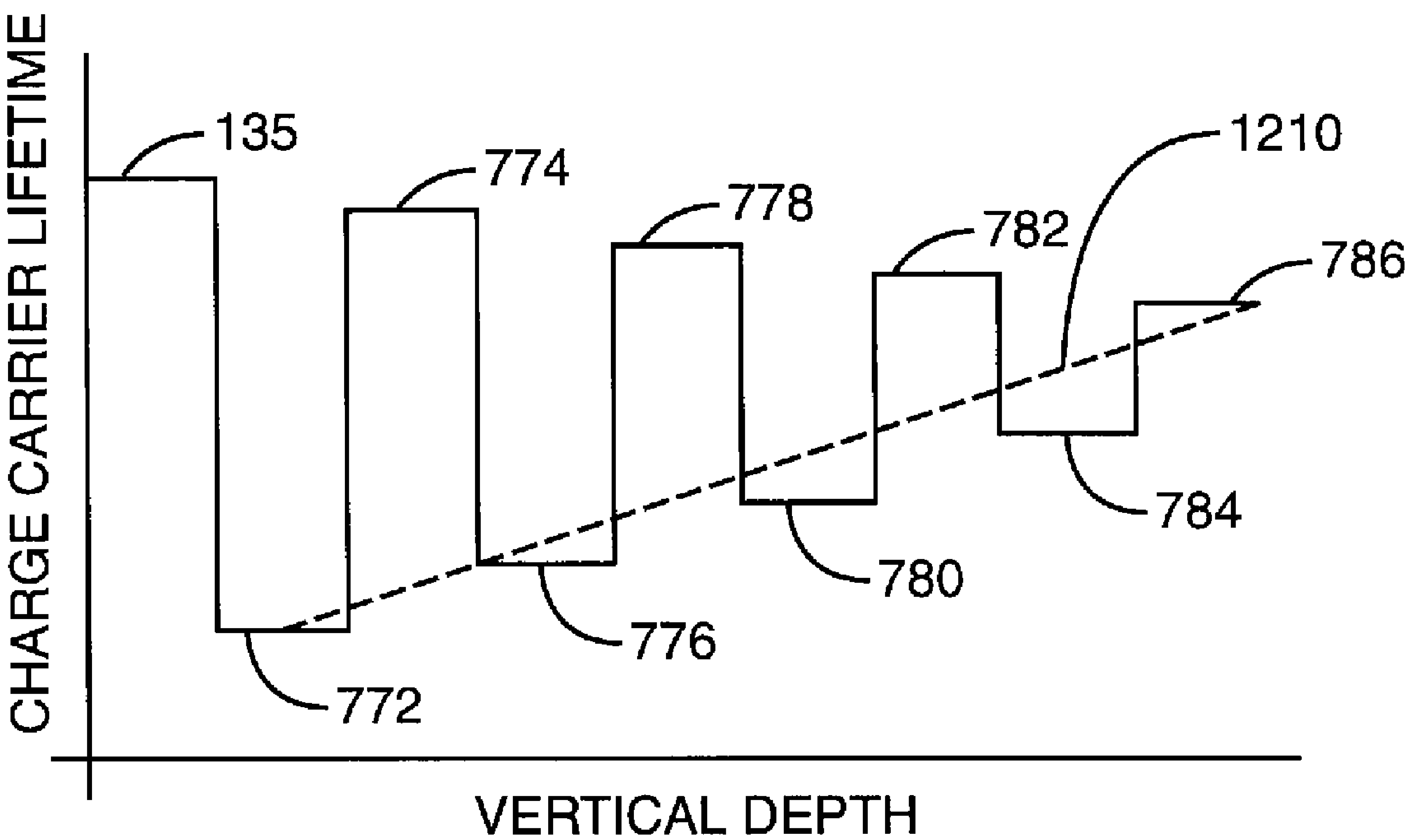
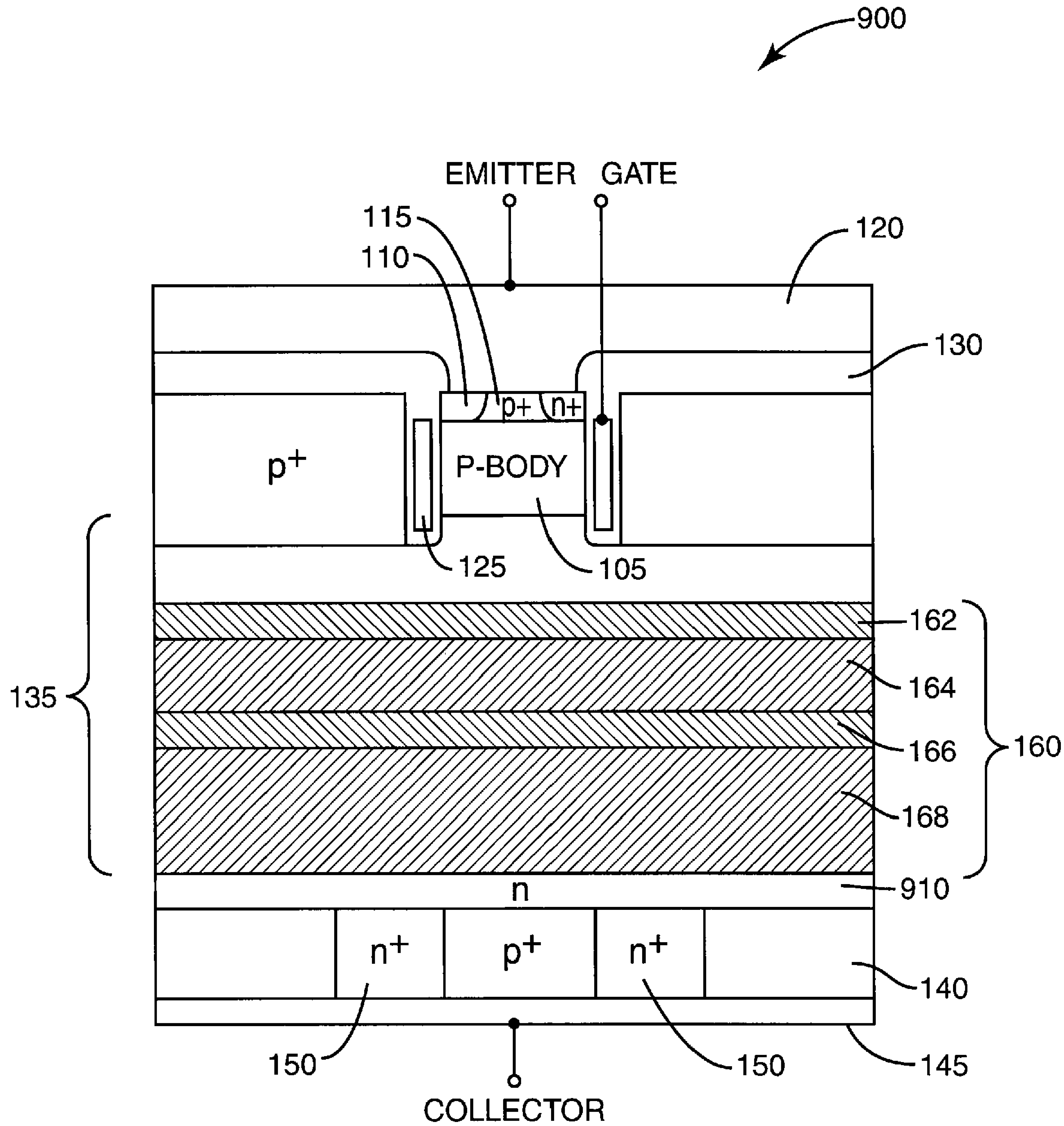

CHARGE CARRIER LIFETIME
135
774
778
782
1210
786
772
776
780
784
VERTICAL DEPTH

FIG. 8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EMITTER
GATE
115
110
120
130
p+
n+
p+
P-BODY
125
105
135
162
164
166
160
168
n
910
n+
p+
n+
140
150
150
145
COLLECTOR

FIG. 9

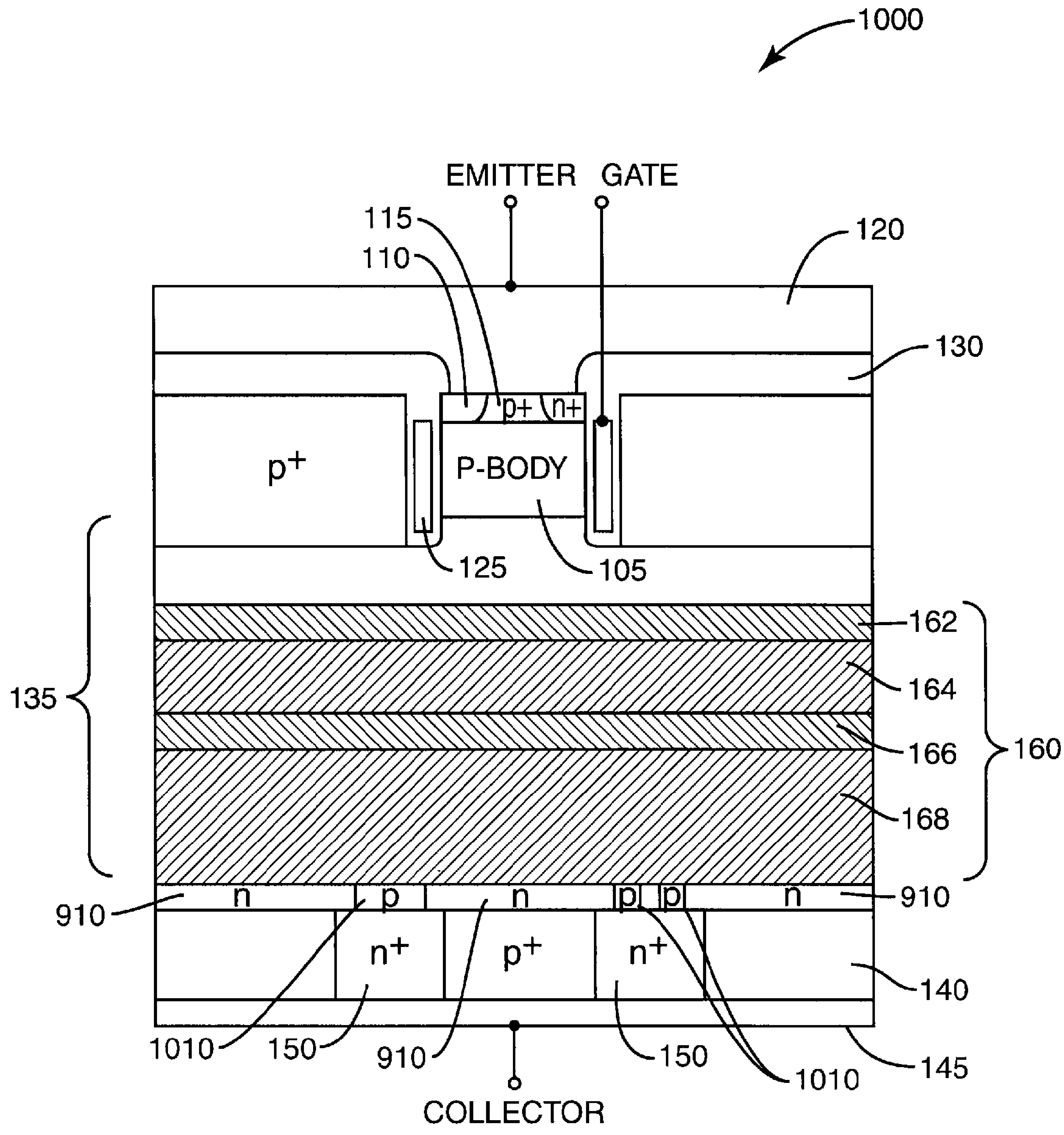

1000
EMITTER
GATE
115
110
120
130
p+
n+
p+
P-BODY
125
105
162
164
135
166
160
168
910
n
p
n
p
p
n
910
n+
p+
n+
140
1010
150
910
150
1010
145
COLLECTOR

FIG. 10

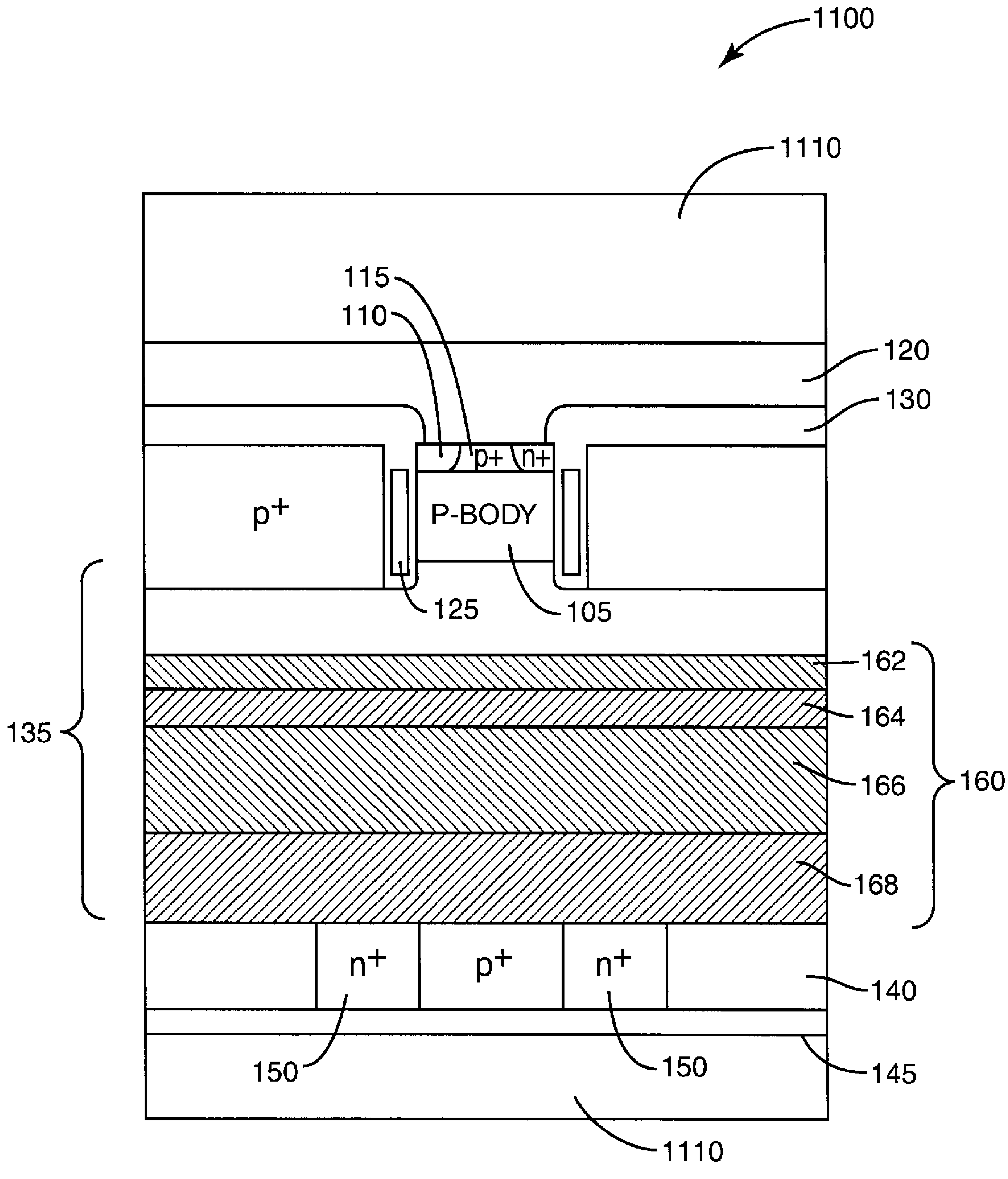

1100
1110
115
110
120
130
p+
n+
p+
P-BODY
125
105
162
164
135
166
160
168
n+
p+
n+
140
150
150
145
1110

FIG. 11

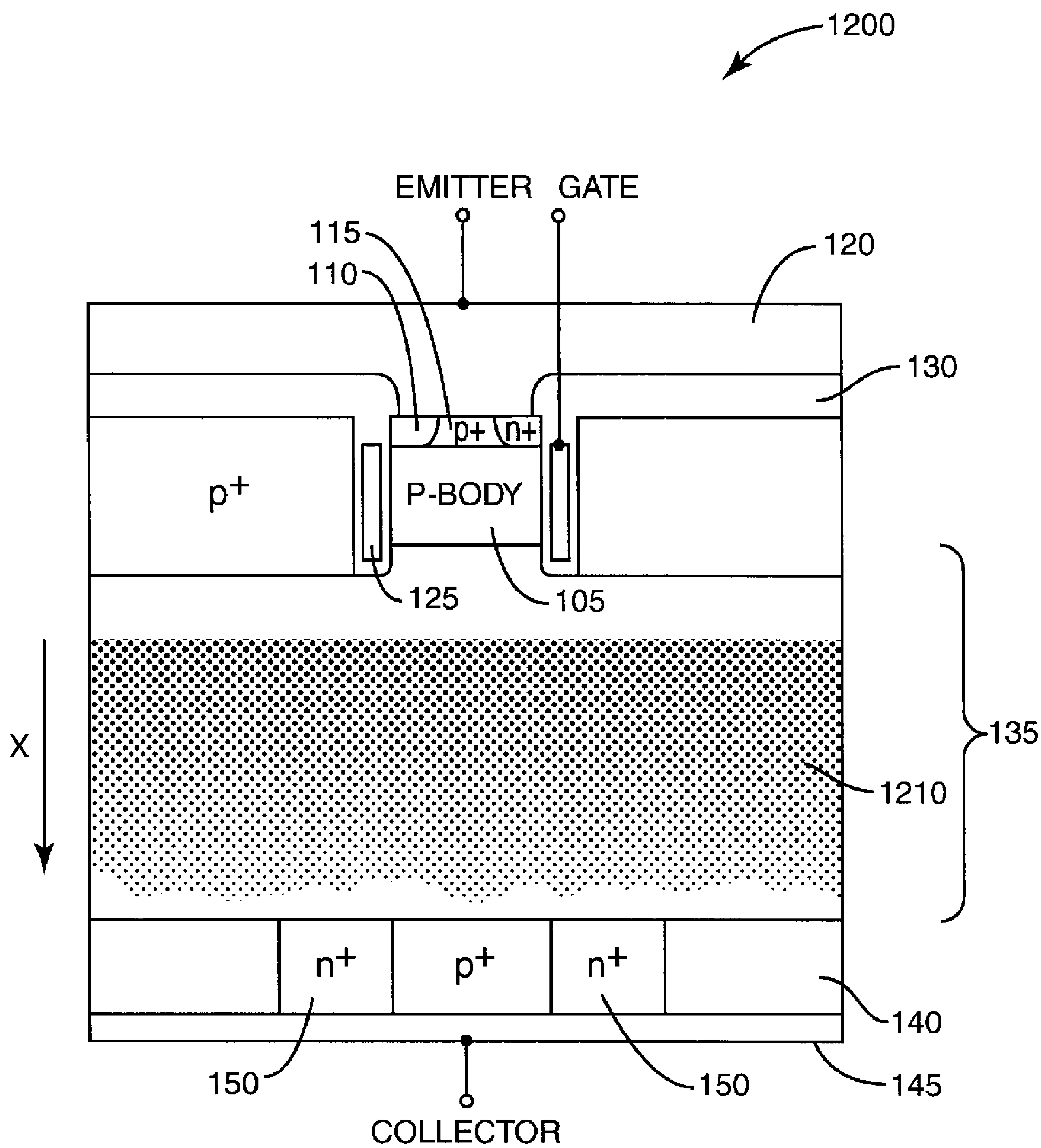
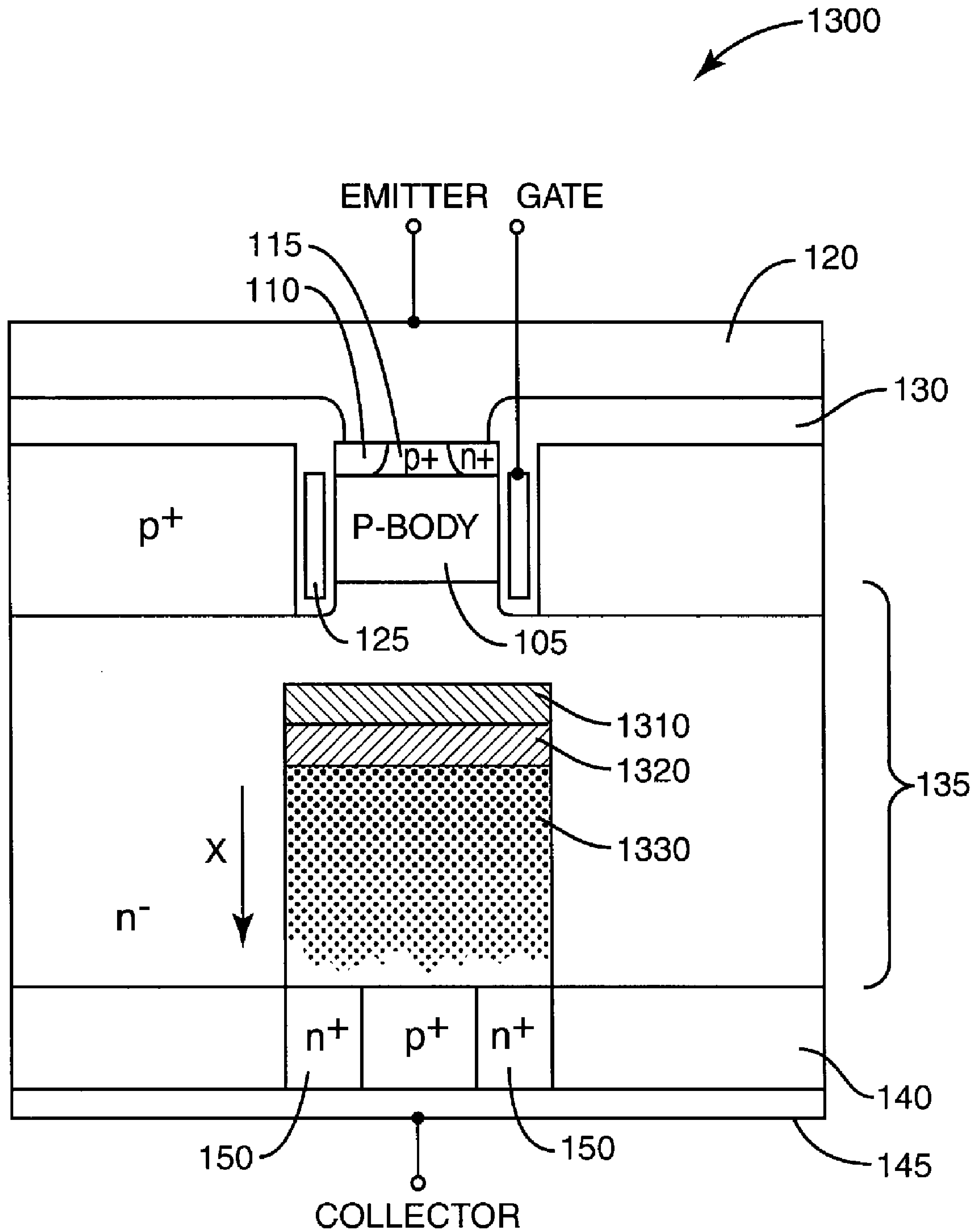

1200
EMITTER
GATE
115
110
120
130
p+
n+
p+
P-BODY
125
105
X
135
1210
n+
p+
n+
140
150
150
145
COLLECTOR

FIG. 12


1300
EMITTER
GATE
115
110
120
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p+
n+
P-BODY
p+
125
105
1310
1320
135
1330
X
n-
n+
p+
n+
140
150
150
145
COLLECTOR

FIG. 13

REDUCED FREE-CHARGE CARRIER LIFETIME DEVICE

BACKGROUND OF THE INVENTION

Insulated-Gate Bipolar Transistors (IGBTs) are three-terminal power semiconductor devices that combine the gate-drive characteristics of a Metal Oxide Semiconductor Field-Effect Transistor (MOSFET) with the high-current and low-saturation-voltage capability of a bipolar transistor. Modern IGBT devices are formed by integrating a FET and a bipolar power transistor on the same silicon die. The FET functions as a control input while the bipolar power transistor is used as a switch. IGBTs efficiently switch electric power in many applications such as electric motors, variable speed refrigerators, air-conditioners, etc. However, these applications have considerably high inductive loads which can cause current to flow in a reverse direction of the switch. If this reverse current is commutated into the IGBT, the device will be destroyed. Therefore, diodes can be used to conduct this reverse current and thereby protect the IGBT.

One technique to enable the IGBT to conduct the reverse current is to integrate a freewheeling diode into the IGBT device. The collector electrode of the IGBT is divided into different regions of n and p-type material. The p-type regions form the IGBT collector. The n-type regions, in conjunction with the n-type drift zone of the IGBT device, form a freewheeling diode with the p-body and a heavily doped p-type anti-latchup region of the IGBT device.

Integrating a freewheeling diode with an IGBT device creates some problematic conditions. Mainly, power continues to dissipate in a freewheeling diode in conduction mode and even after it has been reverse biased. Current will continue to flow until the diode reaches a steady-state reverse bias condition. The condition when the diode changes from forward conduction to blocking is commonly referred to as reverse recovery. The Reverse Recovery Charge (RRC) causes the integrated freewheeling diode to incur electrical losses. These electrical losses increase when the diode is integrated in the IGBT. Some applications cannot tolerate the resulting elevated temperature and/or power conditions. In addition, the elevated temperature and power consumption reduces the lifetime of the IGBT.

Electrical losses caused by integrating a freewheeling diode with an IGBT device can be lowered by reducing the RRC of the diode. Diode RRC can be lowered by reducing the concentration of free-charge carriers within the IGBT device in diode mode. Most free-charge carriers originate within the IGBT device from the highly doped anti-latchup p-type region of the device. This highly doped region injects free-charge carriers into the drift zone of the IGBT device in diode mode. Accordingly, the diode RCC can be reduced by lowering the doping concentration of the highly doped anti-latchup p-type region. However, this significantly reduces the latch-up robustness of the IGBT device and is not a practical solution for most IGBT applications because IGBT performance degrades.

Some conventional approaches involve forming a single or local reduced charge-carrier lifetime region in the drift zone of the IGBT device. This single region must have a very low charge carrier lifetime to sufficiently reduce the RCC of the freewheeling diode integrated with the IGBT device. A single reduced charge-carrier lifetime region is typically formed by irradiating either the front or back side of the wafer on which the IGBT device and freewheeling diode are fabricated. The irradiation treatment may result in two zones being formed within the single reduced charge-carrier lifetime region. One zone has a charge carrier lifetime that is higher than that of the second zone, but lower than that of the non-irradiated part of the IGBT drift zone. However, the single region must still have a very low charge carrier lifetime to be effective at reducing diode RRC. Forming a very low charge carrier lifetime region in the drift zone of an IGBT increases the V_{CESat} (collector-to-emitter saturation voltage) of the IGBT and also leakage current during blocking mode. Moreover, the circuit designer must still trade-off between high emitter efficiency and low diode RRC. Forming a single reduced charge-carrier lifetime region conventionally yields a stored charge that is at least three times higher than that of a single non-freewheeling diode.

SUMMARY OF THE INVENTION

According to one embodiment, a semiconductor device an insulated-gate bipolar transistor having a body region of a first conductivity type, a gate arranged adjacent the body region, a first highly-doped contact region of the first conductivity type arranged in the body region and in contact with a top contact layer, a drift zone of a second conductivity type arranged below the body region, and a second highly-doped contact region of the first conductivity type arranged between the drift zone and a bottom contact layer. The device also comprises a diode having an anode at least partially formed by the body region and a cathode at least partially formed by one or more regions of the second conductivity type formed in the second highly-doped contact region. An irradiation zone is formed in the drift zone. The irradiation zone comprises at least two end of range regions and a reduced charge carrier lifetime region arranged between adjacent end of range regions and between a surface of the drift zone through which the irradiation zone is formed and the end of range region nearest the surface, wherein the reduced charge carrier lifetime regions and the end of range regions each have a charge carrier lifetime lower than that of a non-irradiated region of the drift zone.

Of course, the present invention is not limited to the above features and advantages. Those skilled in the art will recognize additional features and advantages upon reading the following detailed description, and upon viewing the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram of an embodiment of a power semiconductor device including an IGBT having an irradiation zone formed by multiple irradiation treatments.

FIG. **2** is a plot diagram illustrating a charge carrier lifetime profile associated with the device of FIG. **1**.

FIG. **3** is a plot diagram illustrating a charge carrier lifetime profile associated with the device of FIG. **1**.

FIG. **4** is a plot diagram illustrating various charge carrier concentration distributions.

FIG. **5** is a block diagram of an embodiment of a power semiconductor device including an IGBT having an irradiation zone formed by multiple irradiation treatments.

FIG. **6** is a block diagram of an embodiment of a power semiconductor device including an IGBT having an irradiation zone formed by multiple irradiation treatments.

FIG. **7** is a block diagram of an embodiment of a power semiconductor device including an IGBT having an irradiation zone formed by multiple irradiation treatments.

FIG. **8** is a plot diagram illustrating a charge carrier lifetime profile associated with the device of FIG. **7**.

FIG. **9** is a block diagram of an embodiment of a power semiconductor device including an IGBT having an irradiation zone formed by multiple irradiation treatments.

FIG. **10** is a block diagram of an embodiment of a power semiconductor device including an IGBT having an irradiation zone formed by multiple irradiation treatments.

FIG. **11** is a block diagram of an embodiment of a power semiconductor device including an IGBT having an irradiation zone formed by multiple irradiation treatments.

FIG. **12** is a block diagram of an embodiment of a power semiconductor device including an IGBT having an irradiation zone formed by multiple irradiation treatments.

FIG. **13** is a block diagram of an embodiment of a power semiconductor device including an IGBT having an irradiation zone formed by multiple irradiation treatments.

DETAILED DESCRIPTION OF THE INVENTION

FIG. **1** illustrates an embodiment of a power semiconductor device **100** after at least two irradiation treatments. Device **100** includes an Insulated-Gate Bipolar Transistor (IGBT) integrated with a freewheeling diode, together referred to herein as a reverse conducting IGBT (RC-IGBT). The IGBT has a body region **105** of a first conductivity type, e.g., p-type. The body region **105** includes a source region **110** of the opposite conductivity type (e.g., n-type) and a channel. A heavily doped p-type anti-latchup region **115** is arranged in the body region **105** between the source regions **110** and in contact with an emitter contact layer **120**. A gate **125** is arranged adjacent the channel and is separated from the channel and emitter contact layer **120** by an oxide layer **130**. The IGBT also has an n-type drift zone **135** arranged below the body region **105**. A p+ collector contact region **140** is arranged between the drift zone **135** and a collector contact layer **145**, completing the IGBT.

The freewheeling diode integrated with the IGBT has an anode at least partially formed by the body region **105** and the p+ anti-latchup region **115** of the IGBT. The cathode of the freewheeling diode is at least partially formed by one or more n-type regions **150** formed in the p+ doped collector contact region **140**. However, unless the RRC of the freewheeling diode is reduced, the diode may adversely affect IGBT performance.

To this end, an irradiation zone **160** is formed in the drift zone **135** by irradiating the drift zone **135** with at least two irradiation treatments of differing energy levels. In one embodiment, the drift zone **135** is irradiated with protons. In another embodiment, the drift zone **135** is irradiated with helium atoms. Regardless, the irradiation zone **160** has an overall charge carrier lifetime lower than that of the drift zone **135** to reduce diode RRC. In one embodiment, the first irradiation treatment applied to the drift zone **135** is performed at an energy level greater than that of the subsequent irradiation treatment(s). Irradiating the drift zone **135** at two (or more) different energy levels yields at least two end of range regions **162**, **166**.

Each end of range region **162**, **166** is formed in the drift zone **135** at a depth corresponding to the energy level of the respective irradiation treatments. FIG. **1** shows a first end of range region **162** formed at a depth a and a second end of range region **166** formed at a depth b. The first end of range region **162** is formed at a high energy level and is located furthest from the irradiated surface (e.g., the bottom surface of the device **100** in this embodiment). The second end of range region **166** is formed at a lower energy level, and thus is located closer to the irradiated surface. Other end of range regions (not shown) may be formed by irradiating the drift zone **135** with additional treatments.

The irradiation zone **160** also includes a reduced charge carrier concentration region arranged between adjacent end of range regions and between the surface of the drift zone **135** through which the irradiation zone **160** is formed and the end of range region nearest the irradiated surface. In FIG. **1**, a first reduced charge carrier concentration region **164** is arranged between the first and second end of range regions **162**, **166**. A second reduced charge carrier concentration region **168** is arranged between the irradiated surface and the end of range region **166** nearest the irradiated surface. The reduced charge carrier concentration region **164** furthest from the irradiated surface is irradiated once (during the first irradiation treatment) while the other reduced charge carrier concentration region **168** is irradiated twice (during both the first and second irradiation treatments). Thus, the end of range region **162** furthest from the irradiated surface has a charge carrier lifetime much lower than that of the non-irradiated part of the drift zone **135** and which corresponds to the energy level (depth) and dose (carrier lifetime) of the first irradiation treatment as shown in FIG. **2**. The end of range region **166** nearest the irradiated surface also has a charge carrier lifetime much lower than that of the non-irradiated part of the drift zone **135** and which corresponds to the energy level (depth) and dose (carrier lifetime) of both the first and second irradiation treatments as shown in FIG. **2**.

The reduced charge carrier concentration region **164** furthest from the irradiated surface has a relatively constant charge carrier lifetime greater than that of the end of range region **162** furthest from the irradiated surface and less than that of the drift zone **135**, as shown in FIG. **2**. In one embodiment, the charge carrier reduction in region **164** of the irradiation zone **160** is approximately 5% to 20% of that in the end of range region **162** furthest from the irradiated surface. The charge carrier reduction in the reduced charge carrier concentration region **168** nearest the irradiated surface is approximately 5% to 20% of end of range region **162** and approximately 5% to 20% of end of range region **166** because region **168** is irradiated twice. Additional irradiation treatments may be applied to the drift zone **135**, yielding additional end of range regions (not shown) and additional reduced charge carrier concentration regions (also not shown) each having different carrier lifetime reductions corresponding to the energy levels and irradiation doses of the respective additional irradiation treatments. FIG. **3** illustrates another embodiment in which the charge carrier lifetime of end of range region **162** is higher than that of end of range region **166**. Generally, a greater charge carrier reduction is realized nearer regions **105** and **115** of the device **100**, resulting in a suitable RCC of the freewheeling diode even at high diode p-emitter efficiency.

FIG. **4** illustrates how the irradiation zone **160** formed in the power semiconductor device **100** maintains high emitter efficiency while reducing diode RRC as a function of charge carrier lifetime. The x-axis represents vertical depth from the device emitter (i.e., IGBT cathode and diode anode) to the device collector (i.e., IGBT anode and diode cathode). The y-axis represents charge carrier concentration of the device **100** in diode mode (i.e., reverse conduction mode). FIG. **4** shows how carrier concentration changes as a function of vertical depth for four different types of semiconductor devices operating in diode mode. The area under each curve represents the RRC of the diode. Diode RRC is influenced by p-emitter efficiency, charge carrier lifetime, current density, temperature, n-emitter efficiency, etc. Curve **400** shows the carrier concentration of an IGBT without any charge carrier lifetime reduction regions. Curve **420** shows the same device after a single irradiation treatment. Curve **430** shows the power device **100** after at least two irradiation treatments according to the various embodiments disclosed herein. For comparison, curve **410** shows the carrier concentration of a single discrete freewheeling diode with a homogeneously-reduced lifetime and lower p-emitter efficiency.

The irradiation zone **160** reduces the overflow of charge carriers on the front side of the RC-IGBT **100** more than on the back side while in IGBT conduction mode. For example, consider a conventional 600 V RC-IGBT after one or no irradiation treatments. Charge carrier overflow at the location of lowest overflow, which is the location with the highest impact on the forward voltage, is not further reduced for such a conventional RC-IGBT device. To the contrary, the various embodiments described herein provide a first irradiation treatment having an intensity that yields a high charge carrier lifetime reduction end of range region **162** near the front side p-n junction of the RC-IGBT. A second irradiation treatment of a lower intensity affects the charge carrier lifetime in the middle of the drift zone **135** or even near the device collector. Thus, the charge carrier concentration near the device collector can be sufficiently increased while still reducing the RRC of the freewheeling diode. This way, a sufficient IGBT collector-emitter saturation voltage (Vce) can be maintained while still reducing the diode RRC. Furthermore, a higher overall charge carrier lifetime is provided by applying at least two irradiation treatments to the device **100** instead of a single irradiation treatment or no treatment at all, lowering leakage current during blocking mode.

The irradiation dose and energy determines the vertical depth and charge carrier lifetime of the different regions **162-168** of the irradiation zone **160**. In one embodiment, the end of range region **162** furthest from the irradiated surface is located approximately a=10 μm below the upper surface of the drift zone **135** and approximately 4-8 μm below the p-n junction formed between the body region **105** and drift zone **135**. The end of range region **166** nearest the irradiated surface is located, e.g. at approximately half the thickness of the device **100**.

Moreover, the end of range region **162** furthest from the irradiated surface can be produced with a proton dose of approximately 10^{11} to 10^{12} cm^{-2}. The end of range region **166** nearest the irradiated surface can be formed by irradiating the power device **100** with approximately 25%-50% of the dose used to form the other end of range region **162**. This way, the RRC of the freewheeling diode is reduced without adversely affecting the voltage drop in IGBT mode too much. Reduced charge carrier concentration region **164** has a reduction of the carrier lifetime of 5-20% of that in the end of range region **162**. Reduced charge carrier concentration region **168** has a reduction of the carrier lifetime of 5-20% of that in the end of range region **162** plus a further reduction of the carrier lifetime of 5-20% of that in the end of range region **166**, because it is irradiated twice. When helium irradiation is used in place of proton irradiation, the doses identified immediately above can be reduced by approximately 90%.

FIG. **5** illustrates another embodiment of a power semiconductor device **500**. According to this embodiment, the drift zone **135** is irradiated from the upper surface of the device **500** instead of from the lower surface to form an irradiation zone **560**. The irradiation zone **560** includes a first end of range region **562** and a first reduced charge carrier concentration region **564** formed furthest from the irradiated upper surface of the device **500** during a first irradiation treatment. The irradiation zone **560** further includes a second end of range region **566** and a second reduced charge carrier concentration region **568** formed nearer to the irradiated surface during a second irradiation treatment. The device **500** may be subjected to additional irradiation treatments to form more reduced charge carrier concentration regions in the drift zone **135**. The second end of range region **566** may be treated with an intensity of 25%-50% of the intensity used to form the first end of range region **562** as mentioned above. However, any other percentage may apply. Furthermore, the second end of range region **166** may also have a higher dose than the first end of range region **562**. Thus, a reverse order in the location of the charge carrier lifetime minima may apply.

FIG. **6** illustrates yet another embodiment of a power semiconductor device **600** in which the charge carrier lifetime reduction is performed only in the region of the drift zone **135** where the freewheeling diode is active. In this embodiment, during the irradiation treatment steps, a mask (not shown) is used to reduce the charge carrier lifetime of the drift zone **135** only in the approximate region in which the diode will be active. Particularly, the area of the regions **662**, **664**, **666**, **668** of the irradiation zone **660** is approximately limited to the area within the drift zone **135** covered by the n+ regions **150** formed in the p+ collector contact region **140**. Furthermore, the n+ regions **150** can cover a multiplicity of transistor cells with gate **125** and body region **105**. There may be regions of other IGBTs without corresponding n+ regions **125** formed in the p+ collector contact region **140**, i.e. without a freewheeling diode. In one embodiment, the irradiation treatment is masked in these regions.

FIG. **7** shows still another embodiment of a power semiconductor device **700** subjected to four irradiation treatments, yielding an irradiation zone **760** having four end of range regions **772**, **776**, **780** and **784**. A reduced charge carrier concentration region is arranged between adjacent end of range regions and between the irradiated surface (e.g., the bottom surface of the device **700** in this embodiment) and the end of range region **784** nearest the irradiated surface. Particularly, a first reduced charge carrier concentration region **774** is arranged between the two end of range regions **772** and **776** furthest from the irradiated surface and is irradiated only once. A second reduced charge carrier concentration region **778** is arranged between the next two adjacent end of range regions **776** and **780** and is irradiated twice. A third reduced charge carrier concentration region **782** is similarly arranged between end of range regions **780** and **784** and is irradiated three times. The reduced charge carrier concentration region **786** nearest the irradiated surface is arranged between the irradiated surface and the end of range region **784** nearest the irradiated surface. The regions **772-786** are consecutively arranged across the vertical depth of the drift zone **135**, respectively. FIG. **8** shows an example of an associated charge carrier lifetime distribution for the different regions **772-786** of the power semiconductor device **700**.

FIG. **9** illustrates an embodiment of a power semiconductor device **900** having a field stop zone **910** arranged between the reduced charge carrier concentration region **168** nearest the irradiated surface (e.g., the bottom surface of the device **900** in this embodiment) and the p+ doped collector contact region **140**. In one embodiment, the field stop zone **910** is in contact with the bottommost reduced charge carrier concentration region **168**. The field stop zone **910** has a higher doping than that of the drift zone **135** and prevents the electric field that builds up during the blocking state from reaching the p+ doped collector contact region **140**. Accordingly, the substrate thickness may be reduced. The high amount of charge stored by the freewheeling diode is compensated for by reducing the substrate thickness and by reducing the charge carrier lifetime of the drift zone **135** as described herein.

In one embodiment, the field stop zone **910** is created performing one or more proton irradiation steps from the substrate back side followed by a heat treatment between approximately 300-500° C. The heat treatment temperature range may be selected so that the proton irradiation has a doping effect in the form of donators as well as a charge carrier lifetime reduction. The recombination centers created by the heat treatment yield a desirable curvature/bending of the charge carrier profile wherein the selection of the profile of the field stop zone **910** allows for a reduction of the substrate thickness on one hand a soft diode turn-off behavior when commutating on the other hand. This particularly holds true when multiple proton implantations are performed from the substrate back side. In another embodiment, a single or multiple proton implantation is performed followed by annealing at a temperature T**1** to generate the field stop zone **910**. Next, one or more additional proton implantations are performed followed by a second annealing at a temperature T**2** to create a recombination profile. In one embodiment, T**1** is greater than T**2**.

Moreover, the diodes formed in part by the n+ regions **150** formed in the p+ collector contact region **140** may be arranged within a device with multiple transistor cells such that the effective diode area does not overlap with an edge termination structure (not shown). This arrangement prevents electron-hole plasma from occurring below the edge termination structure. Thus, an accumulation of holes beneath the edge termination structure is avoided when the freewheeling diode turns off, which would otherwise limit the safe operating area of the device **900** at high turn-off current.

The field stop zone **910** may be a continuous layer as shown in FIG. **9**. Alternatively, one or more laterally-limited zones **1010** of p-type material can be interspersed throughout the field stop zone **910** as shown in FIG. **10**. Each laterally-limited p-type zone **1010** is arranged above and in contact with one of the n+ regions **150** formed in the p+ collector contact region **140** as shown for example in FIG. **10**. This arrangement provides a reduction of the emitter efficiency of the n+ regions **125**, reducing the RRC. Nevertheless the diode softness will be improved. However, the emitter efficiency cannot be reduced without limit via the n implantation dose because a surface concentration of at least $5 \cdot 10^{19}$ cm^{-3} is desired to form an ohmic contact. The laterally-limited p-type zones **1010** also lead to the creation of electron-hole pairs by avalanche multiplication at the p-n junction when the electric field is high. These additionally generated charges can cause a continuing current flow and a soft commutation behavior, wherein otherwise the depletion of stored charge would lead to a current tear-off.

FIG. **11** illustrates yet another embodiment of a power semiconductor device **1100** where a metal layer **1110** is formed on top of at least the front side and/or the back side of the device. According to one embodiment, the metal layer **1110** is a copper layer which is relatively thick, for example 20 μm in one embodiment. However, other metals can be used. In one embodiment, the metal layer is formed from any metal having a specific heat capacity at least approximately ⅔ that of copper. The thickness of each copper layer **1110** can be selected such that they serve not only as a mere metallization layer but also provide a sufficiently large heat capacity. Thus, the heat capacity could be at least 10% of the heat capacity of the silicon within the device **1100**. The emitter contact layer **120** can also be part of the top copper layer **1110**.

Forming the metal layer **1110** on top of at least the front side and/or the back side of the device **1100** provides for a very homogeneous current imprint, particularly for high current loads such as a surge current or a shorting of the IGBT. Moreover, the high heat capacity of the metal layer(s) **1110** allows for a temporary storage of dissipated energy. Thus, higher energy is needed to damage or destroy the power device **1100** after termination of a short circuit pulse. This increases the number of applications for which the power device **1100** may be used.

FIG. **12** shows another embodiment of a power semiconductor device **1200** with a step-less reduced charge carrier concentration region **1210** formed in the drift zone **135**. The region **1210** is step-less in that abrupt changes in charge carrier lifetime are not present in the region **1210**. Instead, the step-less region **1210** has a continuously increasing charge carrier lifetime in the vertical direction indicated by line X. Charge carrier lifetime reduction is most prevalent near the p-n junction formed between the body region **105** and drift zone **135**, gradually increasing in the vertical direction heading toward the device collector. This way, diode RRC is reduced without adversely affecting emitter efficiency as previously described herein. The step-less region **1210** may be formed in approximation by a plurality of local charge carrier reductions or a gradual or stepwise decrease in irradiation energy. The dashed line in FIG. **8** shows an example of a corresponding charge carrier lifetime profile.

FIG. **13** shows another embodiment of a power semiconductor device **1300** in which local charge carrier reduction regions **1310**, **1320** near the front-side p-n junction side are combined with a step-less reduced charge carrier concentration region **1330**. Step-less region **1330** can again be created by multiple regions as discussed above. This embodiment approaches the characteristic profile of a diode with homogeneous distribution of charge carrier lifetime for an RC-IGBT when in diode mode despite the strong emitter created by p+ region **115**. Depending on the location of the step-less reduced charge carrier concentration region **1330**, any suitable diode profile having a homogeneous charge carrier lifetime distribution can be approached.

With the above range of variations and applications in mind, it should be understood that the present invention is not limited by the foregoing description, nor is it limited by the accompanying drawings. Instead, the present invention is limited only by the following claims and their legal equivalents.

What is claimed is:

1. A semiconductor device, comprising:

an insulated-gate bipolar transistor having a body region of a first conductivity type, a gate arranged adjacent the body region, a first highly-doped contact region of the first conductivity type arranged in the body region and in contact with a top contact layer, a drift zone of a second conductivity type arranged below the body region, and a second highly-doped contact region of the first conductivity type arranged between the drift zone and a bottom contact layer;

a diode having an anode at least partially formed by the body region and a cathode at least partially formed by one or more regions of the second conductivity type formed in the second highly-doped contact region; and

an irradiation zone formed in the drift zone, the irradiation zone comprising at least two end of range regions and a reduced charge carrier lifetime region arranged between adjacent end of range regions and between a surface of the drift zone through which the irradiation zone is formed and the end of range region nearest the surface, wherein the reduced charge carrier lifetime regions and the end of range regions each have a charge carrier lifetime lower than that of a non-irradiated region of the drift zone.

2. The semiconductor device of claim 1, wherein the charge carrier lifetime of the end of range region arranged closest to the body region is lower than the charge carrier lifetime of the end of range region arranged closest to the second highly-doped contact region.

3. The semiconductor device of claim 2, wherein the charge carrier lifetime of the end of range region arranged closest to the body region is approximately the same as the charge carrier lifetime of the end of range region arranged closest to the second highly-doped contact region.

4. The semiconductor device of claim 2, wherein the charge carrier lifetime of the reduced charge carrier concentration region arranged closest to the body region is higher than the charge carrier lifetime of the reduced charge carrier concentration region arranged closest to the second highly-doped contact region.

5. The semiconductor device of claim 1, wherein the charge carrier lifetime of the end of range region arranged closest to the body region is higher than the charge carrier lifetime of the end of range region arranged closest to the second highly-doped contact region.

6. The semiconductor device of claim 5, wherein the charge carrier lifetime of the reduced charge carrier concentration region arranged closest to the body region is higher than the charge carrier lifetime of the reduced charge carrier concentration region arranged closest to the second highly-doped contact region.

7. The semiconductor device of claim 1, wherein the irradiation zone is limited to an area approximately within the drift zone where the diode is active.

8. The semiconductor device of claim 7, wherein the one or more regions of the second conductivity type formed in the second highly-doped contact region are limited to an area approximately within the second highly-doped contact region covered by the irradiation zone.

9. The semiconductor device of claim 1, further comprising a field stop zone of the second conductivity type arranged between the second highly-doped contact region and the end of range region arranged closest to the second highly-doped contact region.

10. The semiconductor device of claim 9, further comprising one or more laterally-limited zones of the first conductivity type embedded in the field stop zone over each region of the second conductivity type formed in the second highly-doped contact region.

11. A semiconductor device, comprising:

an insulated-gate bipolar transistor having a body region of a first conductivity type, a gate arranged adjacent the body region, a first highly-doped contact region of the first conductivity type arranged in the body region and in contact with a top contact layer, a drift zone of a second conductivity type arranged below the body region, and a second highly-doped contact region of the first conductivity type arranged between the drift zone and a bottom contact layer;

a diode having an anode at least partially formed by the body region and a cathode at least partially formed by one or more regions of the second conductivity type formed in the second highly-doped contact region;

a first end of range irradiation region formed in the drift zone below the body region;

a second end of range irradiation region formed in the drift zone below the first end of range irradiation region;

a first reduced charge carrier concentration region formed in the drift zone between the first and second end of range irradiation regions;

a second reduced charge carrier concentration region formed between a surface of the drift zone through which the end of range irradiation regions are formed and the end of range region nearest the surface; and

wherein the end of range irradiation regions and the reduced charge carrier concentration regions each have a charge carrier lifetime lower than a charge carrier lifetime of a non-irradiated region of the drift zone.

12. A method of fabricating a semiconductor device, comprising:

forming within a semiconductor substrate an insulated-gate bipolar transistor having a body region of a first conductivity type, a gate arranged adjacent the body region, a first highly-doped contact region of the first conductivity type arranged in the body region and in contact with a top contact layer, a drift zone of a second conductivity type arranged below the body region, and a second highly-doped contact region of the first conductivity type arranged between the drift zone and a bottom contact layer;

forming a diode having an anode at least partially formed by the body region and a cathode at least partially formed by one or more regions of the second conductivity type formed in the second highly-doped contact region; and

irradiating the drift zone to form at least two end of range regions in the drift zone and a reduced charge carrier lifetime region arranged between adjacent end of range regions and between a surface of the drift zone through which the drift zone is irradiated and the end of range region nearest the surface, wherein the reduced charge carrier lifetime regions and the end of range regions each have a charge carrier lifetime lower than that of a non-irradiated region of the drift zone.

13. The method of claim 12, wherein irradiating the drift zone comprises:

irradiating a back side of the semiconductor substrate to form one of the end of range regions in the drift zone closest to the body; and

irradiating the back side of the semiconductor substrate to form a different one of the end of range regions in the drift zone closest to the second highly-doped contact region.

14. The method of claim 12, wherein irradiating the drift zone comprises:

irradiating a front side of the semiconductor substrate to form one of the end of range regions in the drift zone closest to the body; and

irradiating the front side of the semiconductor substrate to form a different one of the end of range regions in the drift zone closest to the second highly-doped contact region.

15. The method of claim 12, wherein irradiating the drift zone comprises irradiating the semiconductor substrate so that the charge carrier lifetime of the end of range region arranged closest to the body region is lower than the charge carrier lifetime of the end of range region arranged closest to the second highly-doped contact region.

16. The method of claim 12, wherein irradiating the drift zone comprises irradiating the semiconductor substrate so that the charge carrier lifetime of the end of range region arranged closest to the body region is higher than the charge carrier lifetime of the end of range region arranged closest to the second highly-doped contact region.

17. The method of claim **12**, further comprising forming a field stop zone of the second conductivity type between the second highly-doped contact region and the end of range region arranged closest to the second highly-doped contact region.

18. The method of claim **17**, further comprising forming one or more laterally-limited zones of the first conductivity type in the field stop zone over each region of the second conductivity type formed in the second highly-doped contact region.

19. The method of claim **12**, wherein irradiating the drift zone comprises irradiating the drift zone in an area where the diode is active.

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